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International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 4 : G01N 21/88 | A1 | (11) International Publication Number: WO 85/ 03353

(43) International Publication Date: 1 August 1985 (01.08.85)

(21) International Application Number: PCT/US85/00082

(22) International Filing Date: 16 January 1985 (16.01.85)

(31) Priority Application Number: 573,816

(32) Priority Date: 25 January 1984 (25.01.84)

(33) Priority Country: US

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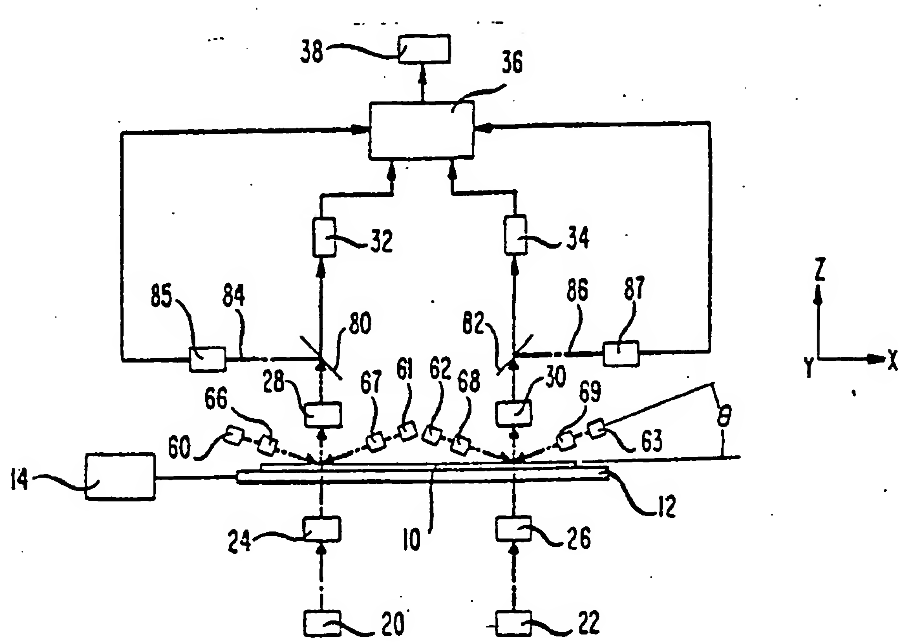
(81) Designated States: AT (European patent), BE (European patent), CH (European patent), DE (European patent), FR (European patent), GB (European patent), JP, LU (European patent), NL (European patent), SE (European patent).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: INSPECTION SYSTEM UTILIZING DARK-FIELD ILLUMINATION



(57) Abstract

For inspecting photolithographic masks, and the like, of the type comprising an ordered mosaic of identical patterns on a substrate (10) surface, corresponding portions or features (42, 44) of pairs of patterns are simultaneously illuminated by dark-field illumination (60-69) (incident light rays almost parallel to the surface) to cause light scattering from edges only of the features and of any defects associated therewith. The presence of a defect (40) in or at one of the features gives rise to a difference in the light scattering characteristic from the two features, which difference provides an error signal indicative of the presence of a defect.

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INSPECTION SYSTEM UTILIZING DARK-FIELD ILLUMINATION

Background of the Invention

This invention relates to methods and apparatus for inspecting patterned workpieces, particularly lithographic masks and reticles used in the fabrication of integrated circuit semiconductor wafers and/or for inspecting the wafers themselves.

Feature widths on masks and reticles used in making integrated circuits have continued to shrink, e.g., as low as 0.5 μm.

Ideally, workpieces such as masks, reticles and wafers should be inspected for defects down to about half the minimum feature size. In practice, though, this is often not possible. For example, one commercially available mask inspection system is capable of detecting a minimum-size defect of only about one μm, and this capability degrades to about two μm in complex areas of the mask under inspection. (Hereinafter, the term "mask" is to be construed to mean either a mask or a reticle. Also, the invention is applicable to the inspection of other patterned workpieces, e.g., semiconductor wafers.)

Conventional systems accomplish mask inspection by bright-field illumination of a portion of a pattern on the mask. A signal derived therefrom is compared with another signal representative of a corresponding portion of another supposedly identical pattern (both patterns, for example, along with many others, being disposed in an ordered mosaic on the mask). Because the patterns are supposedly identical, differences between the two signals are indicative that one of the portions is defective.

In practice, the minimum-size defect that can be detected by an inspection system of the aforespecified type is set by false error indications arising from misalignment between the patterns being compared. At a given misalignment, the minimum detectable defect is defined as the defect which produces a signal as large as the false

signal arising from the misalignment.

Misalignment between the patterns may arise from residual alignment errors in the inspection systems, mismatched optical distortions, mask distortions, linewidth variations, etc. The present invention is directed to means for reducing the effects of such misalignments.

Summary of the Invention

Workpiece patterns to be compared are illuminated in a dark-field mode in which incident light is directed at the surface of the workpiece at a glancing angle. In such a mode, only light scattered from the edges of a feature or defect is detected. For a given misalignment, the ratio of defect signal-to-misalignment signal for relatively small defects is found to be much greater with dark-field illumination than with conventional bright-field illumination. Hence, dark-field illumination in an inspection system provides a basis for greatly increasing the detectability of small defects.

Brief Description of the Drawing

FIG. 1 depicts a known mask inspection system;

FIG. 2 represents two compared mask areas one of which contains a defect;

FIG. 3 represents features in two compared mask areas and illustrates a misalignment therebetween;

FIG. 4 is a schematic representation of a mask inspection system in accordance with the present invention;

FIG. 5 shows the manner in which incident light is scattered by and collected from a feature or defect illuminated in the dark-field mode;

FIG. 6 shows an alternative way of providing dark-field illumination in the FIG. 4 system;

FIG. 7 is a top view of a portion of the FIG. 4 system; and

FIG. 8 is a top view of a portion of a modification of the FIG. 4 system.

Detailed Description

In the conventional system schematically depicted in FIG. 1, a standard workpiece 10 to be inspected is shown supported on a table 12. The table is mechanically coupled to an XY drive assembly 14.

For illustrative purposes, the workpiece 10 of FIG. 1 is a mask. The mask 10 comprises an optically transparent substrate having thereon optically opaque features, e.g., of chromium. These features define at least two supposedly identical patterns on the mask.

In the FIG. 1 system, two spots of light are directed along dot-dash reference lines 16 and 18 through openings through the table 12 at the underside of the mask 10. The spacing of the spots is equal to the pattern spacing, or a multiple thereof, so that the spots are directed at corresponding, presumably identical portions or features of identical patterns.

The light spots are provided by conventional sources 20, 22 and respectively associated lens assemblies 24, 26.

By means of the assembly 14, the table 12 of FIG. 1 is indexed in the X and Y directions for inspecting successive pairs of patterns on the mask.

The amount of incident light that is propagated through the mask 10 is dependent on the transmissive character of the pattern in each illuminated area.

In the conventional so-called bright-field-illumination mode represented in FIG. 1, light transmitted through the illuminated patterned areas of the mask 10 is collected by lens assemblies 28 and 30 which comprise, for example, conventional microscope objectives. In turn, this collected light is focused onto standard photodetector arrays 32 and 34 which provide electrical output signals representative of the illuminated mask patterns.

The signals provided by the arrays 32, 34 are compared and processed in a standard signal processor and minicomputer unit 36, and viewed from a display 38.

Assume that the viewing optics of the inspection

system are characterized by a Gaussian point spread function whose full-width at half maximum (FWHM) is w. (The value w also constitutes the so-called resolution element of the viewing optics.) Assume further that one of the spaced-apart patterns being inspected contains a centrally located opaque circular defect 40 of diameter d, as depicted in FIG. 2.

In the standard bright-field mode of mask illumination, it is apparent that the photodetector array responsive to light transmitted through the left-hand pattern that contains the opaque defect 40 (FIG. 2) receives less light than the other photodetector array. As a result, a bright-field difference signal B_{def} attributable to the defect 40 is generated in the unit 36 of FIG. 1. When d/w is small, B_{def} can be approximated by the expression

$$K_1 I_0 d^2 \qquad (1)$$

where K_1 is a constant and I_0 is the peak value of the point spread function at the photodetector array. (The constants K_1, K_2, K_3 and K_4 employed herein are roughly of the same order of magnitude.)

As mentioned above, difference signals are generated in the mask inspection systems even in the absence of defects. Thus, for example, relative misalignment between features in the patterns being compared also produces a difference signal. In practice, such misalignment-caused signals set the value of the minimum-size defect that can be detected by the inspection system.

FIG. 3 represents portions of two identical opaque features 42 and 44 included in spaced-apart patterns, each feature including a straight edge 46 and 48, respectively. With perfect alignment, the edges of the two features are disposed at identical corresponding points. Thus, for example, the right-hand edge 46, 48 of each ideal

feature would extend through the center 50, 52 of its respective light spot 54 and 56. In this ideal case, the transmitted light associated with each of the light spots 54, 56 would be exactly the same. Hence, no difference signal (false defect signal) would be thereby generated by the unit 36 of FIG. 1.

But, as specified earlier above, perfect alignment is rarely, if ever, achieved in practice. This is also represented in FIG. 3 wherein the edge of the feature 42 is assumed, because of misalignment by a distance "a" relative to the aforespecified ideal condition, to lie along dashed line 58.

As a consequence of such misalignment, the photodetector array responsive to bright-field light transmitted through the left-hand pattern receives less light than the other photodetector array. As a result, a bright-field difference signal B_{mis} attributable to the misalignment "a" is generated. When a/w is small, B_{mis} can be approximated by the expression

$$K_2 I_0 aw \qquad (2)$$

where K_2 is a constant.

Roughly speaking, when the speckled area in FIG. 3 attributable to misalignment approximately equals the area of the defect 40 of FIG. 2, the difference signal B_{mis} approximately equals the difference signal B_{def}. This is evident from a consideration of equations (1) and (2).

In one illustrative bright-field system in which w = 1 μm (Gaussian illumination) and d = 0.52 μm, B_{mis} approximately equals B_{def} for a misalignment "a" of about 0.2 μm. That is, in such prior art system, for a misalignment of about 0.2 μm, the minimum detectable defeat has a value of d = 0.52 μm.

In accordance with the present invention, the patterns being compared are illuminated in a dark-field

mode, as depicted in FIG. 4. By "dark-field" illumination is meant illumination in a non-normal, glancing direction. In effect, dark-field illumination outlines only the edges of features or defects on the mask. Because of this, when viewed from above, the mask surface (the "field"), although illuminated by incident light, appears dark except for visible bright lines corresponding to feature or defect edges.

In Fig. 4, the dark-field is provided by four light sources 60 through 63 and associated lens assemblies 66 through 69 which together serve to illuminate corresponding portions of two patterns on the mask 10.

Advantageously, for reasons later described, the illumination provided by the sources 60 through 63 is selected to be within a specified wavelength band. This is accomplished, for example, with a mercury arc lamp and an associated filter. Alternatively, each source can constitute a laser.

Advantageously, the angle θ at which light is directed at the mask 10 in the dark-field mode is in the range of 0-to-75 degrees. Illustratively, the angle θ is selected to be approximately 5 degrees.

For reasons later described, the FIG. 4 system also advantageously includes a bright-field-illumination capability of the type described above in connection with FIG. 1.

In the dark-field mode of operation, only light scattered from illuminated edges of a feature or defect is collected. Light incident on other surfaces of the features or defects is reflected and/or refracted along paths that do not fall within the entrance aperture of the collecting optics.

This is illustrated in FIG. 5, wherein feature or defect 70 on one pattern on the workpiece 10 is obliquely illuminated by light beams directed thereat along center lines 72, 74. Illustratively, each beam illuminates an area approximately 300 μm in diameter on the workpiece

surface.

Light scattered from the edges of the feature or defect 70 is represented by lines 76, 78. Only such scattered light is collected by the lens assembly 28.

Scattered light collected by the lens assemblies 28, 30 is directed (FIG. 4) at dichroic mirrors 80, 82. These mirrors reflect light of wavelength emitted by the dark-field-illumination sources 60 through 63. On the other hand, bright-field illumination provided by the sources 20, 22 at a different wavelength propagates straight through the mirrors 80, 82 to the photodetector arrays 32, 34. (Other known techniques such as polarization separation are available for separating bright-field and dark-field illumination.)

Dark-field-derived light reflected by the mirrors 80, 82 is propagated along paths 84, 86 to respective photodetector arrays 85, 87. In turn, electrical signals generated by the arrays 85, 87 are applied to the unit 36.

Considering, for example, the dark-field illumination of the two pattern portions shown in FIG. 2, the photodetector array 85 responsive to light from the left-hand portion that contains the opaque defect 40 receives more scattered light than does the photodetector array 87 which is responsive to light from the right-hand portion which contains no edges to scatter light toward the lens assembly 30 of FIG. 4. As a result, a dark-field difference signal D_{def} attributable to the defect 40 is generated. When d/w is small, D_{def} can be approximated by the expression

$$K_3 J_0 d \qquad (3)$$

where K_3 is a constant and J_0 is the intensity per unit length of the edge source of the scattered light. For very large centrally positioned defects (d/w>>1), D_{def} becomes small because the defect edge lies outside the

light spot.

For the particular misalignment condition represented in FIG. 3, assuming the light spots 54 and 56 are from the dark-field light sources 60-63, the length of the feature edge lying within the light spot 54 on the left-hand portion is less than the length of the feature lying within the light spot 56 on the right-hand portion. Hence, the photodetector array 87 responsive to scattered light from the right-hand portion receives more light than does the photodetector array 85 responsive to scattered light from the left-hand portion. As a result, a dark-field difference signal D_{mis} attributable to the misalignment a is generated in the unit 36 of FIG. 4. When a/w is small, D_{mis} can be approximated (for Gaussian illumination) by the expression

$$K_4 J_0 a \qquad (4)$$

where K_4 is a constant.

Significantly, for a given misalignment, the ratio of defect signal-to-misalignment signal is much greater for dark-field illumination than it is for bright-field illumination. This can be seen, for example, from FIG. 3. For a given misalignment "a", the misalignment signal B_{mis} for bright-field illumination is a function of the area aw (equation 2), whereas the misalignment signal D_{mis} for dark-field illumination is a function merely of the linear misalignment dimension "a" (equation 4). Although the strength of the defect signal is smaller for dark-field illumination than for bright-field illumination, still, as noted, the net result is that the ratio of defect signal to misalignment signal is greater with the dark-field illumination. In other words, for a given misalignment, a mask inspection system embodying dark-field illumination can detect defects that are considerably smaller than those detectable in a bright-field system.

In one specific illustrative dark-field system in which w = 1 μm and a = 0.2 μm (the same misalignment mentioned above for bright-field illumination), D_{def} approximately equals D_{def} when the diameter d of a defect has a value of only about 0.11 μm. Thus, in this particular example, the diameter of the minimum-size defect detectable in the dark-field inspection mode is less than four times that of the minimum-size defect detectable in the conventional bright-field mode. The gain in sensitivity with dark-field illumination is even greater for smaller misalignments.

In the system shown in FIG. 4, dark-field illumination of two spaced-apart regions on the mask 10 is achieved by utilizing sources 60 through 63 positioned above the surface of the mask. Alternatively, dark-field illumination can be implemented by positioning the sources and associated lens assemblies below the mask. A portion of a system that embodies this alternative approach is schematically depicted in FIG. 6.

FIG. 7 is a simplified top view of a portion of the FIG. 4 system. All the light from the dark-field light sources 60-63 (sources 61 and 62 not being shown) are directed along the X-axis of the table 12. In FIG. 8, the light sources are off-set by an angle θ_1 (not critical, but generally in a range of 1 to 20 degrees) from the X-axis. Generally (although a function of the geometry of the features on the workpiece), the arrangement of FIG. 8 has a greater defect detection sensitivity than that of the FIG. 7 arrangement. The reason is as follows.

The defect detect sensitivity is a function of the difference in the amount of light received from the two pattern features being inspected, such difference being caused by the presence of a defect (i.e., any difference between the features). The detection sensitivity can be increased if the proportion of the total light received by the light detectors owing to the presence of the defect is increased. This is accomplished in the FIG. 8

arrangement.

The amount of light scattered from a feature or defect edge in any direction is a function of the angle of incidence of the light with respect to the edge. Thus, for example, for feature edges aligned in the X and Y directions, the amount of light scattered in the X-Z plane towards the detector 28 (disposed in the X-Z plane, FIG. 4) is greater in the FIG. 7 arrangement than in the FIG. 8 arrangement owing to the differences in the angle of incidence of the illumination against the feature edges. Accordingly, for such feature edge orientations, the total amount of dark-field illumination reaching the detectors is less in the FIG. 8 arrangement than in the FIG. 7 arrangement. However, for defects, which generally have irregular shapes, the total amount of light scattered from the defect edges towards the light detectors is little affected by the angle θ_1 and, generally, the same amount of light will be scattered by the defect edges in the X-Z plane in either of the FIG. 7 and 8 arrangements. Thus, because the light scattered from the X-Y oriented feature edges towards the light detector in the FIG. 8 arrangement is less than that scattered from these feature edges in the FIG. 7 arrangement, the light scattered from the defect edges in the FIG. 8 arrangement is a larger proportion of the total light received by the detectors than in the FIG. 7 arrangement.

In practice, the vast majority of edges of features of most masks extend along preferred directions, e.g., along the X and Y axes shown in FIGs. 7 and 8. Thus, in such situations, the FIG. 8 arrangement provides greater defect detection sensitivity.

Although dark-field illumination greatly increases the detectability of small defects, it is generally advantageous to retain some bright-field capability even at a reduced sensitivity of the dark-field system. This is because the bright-field system is better able to detect large defects.

The inspection systems rely upon a comparison of the light from two patterns. Both patterns need not be on the same workpiece, and one of the patterns, where ever located, can be a standard against which the other patterns, one by one, are compared. Also, the standard can comprise simply a train of signals against which the detected signals are compared.

Claims

1. Apparatus for inspecting a workpiece to determine whether or not a first region thereof is patterned in accordance with prescribed design standards, said apparatus comprising -

means for illuminating said region to cause light to be transmitted therefrom,

means for collecting such transmitted light and providing a first output signal representative of the pattern of said region,

means for providing a comparison signal derived from a second region supposedly identical to said first region, and

means for comparing said signals to provide an indication of whether or not said first region is patterned in accordance with said second region and thus in accordance with said prescribed design standards,

characterized by means (60, 66, 67 61) for illuminating said first region (42) by dark-field illumination, said transmitted light thus comprising light scattered from edges (46) of said first region.

2. Apparatus as in claim 1 wherein said second region (44) is disposed on said workpiece, and said comparison signal is obtained using means (63, 69, 68, 62, 30, 82, 87) separate from but identical to the means used to provide said first output signal.

3. Apparatus as in claim 1 wherein said second region is disposed on another workpiece, and said comparison signal is obtained using means (63, 69, 68, 62, 30, 82, 87) separate from but identical to the means used to provide said first output signal.

4. Apparatus as in claim 1 wherein said comparison signal is a stored signal representative of said second region.

5. Apparatus as in claims 1-3 further including means (20, 24) for illuminating said first region in a bright-field mode,

means (32) responsive to bright-field-mode light transmitted from said first region for providing a second output signal also representative of the pattern of said first region, and

means (80) for distinguishing between dark-field-mode scattered light and bright-field-mode transmitted light for generating said first and second output signals in response to said scattered and transmitted light, respectively.

6. Apparatus as in claims 1-4 wherein different edges of said first region extend along preferred (x-y) axes, and wherein the direction (θ_1) of incident dark-field illumination is selected to minimize collectible light scattered from said edges.

7. A method of inspecting a workpiece to determine whether or not a first region thereof is patterned in accordance with prescribed design standards, said method comprising the steps of

illuminating said first region to cause light to be transmitted therefrom,

collecting such transmitted light for providing a first output signal representative of the pattern of said region,

providing a comparison signal derived from a second region supposedly identical to said first region

and comparing said signals to provide an indication of whether or not said first region is patterned in accordance with said second region and thus in accordance with said prescribed design standards,

characterized by illuminating said first region in a dark-field illumination mode.

8. A method as in claim 7 wherein said second region is disposed on said workpiece, and said comparison signal is obtained using method steps identical to those used to provide said first output signal.

9. A method as in claim 7 wherein said second region is disposed on another workpiece, and said

comparison signal is obtained using method steps identical to those used to provide said first output signal.

10. A method as in claim 7 wherein said comparison signal is a stored signal representative of said second region.

FIG. 1
(PRIOR ART)

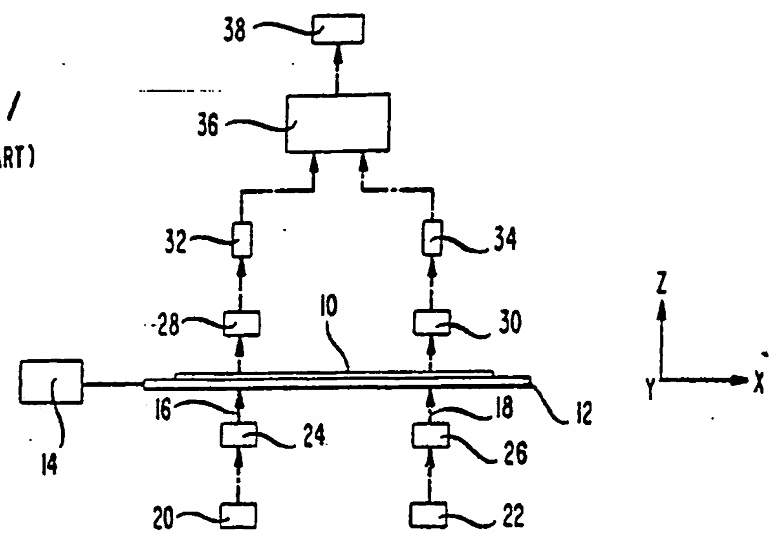

FIG. 2
SPACED-APART AREAS BEING COMPARED

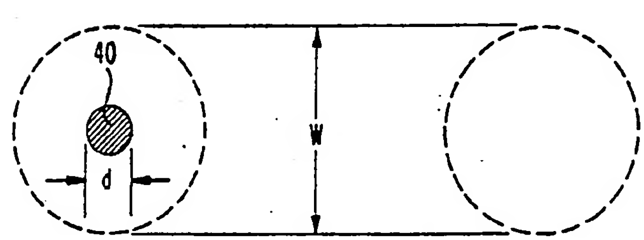

FIG. 3

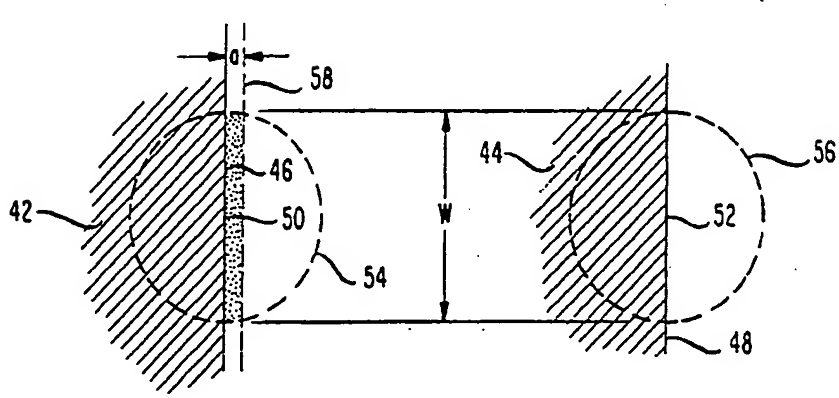

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FIG. 4

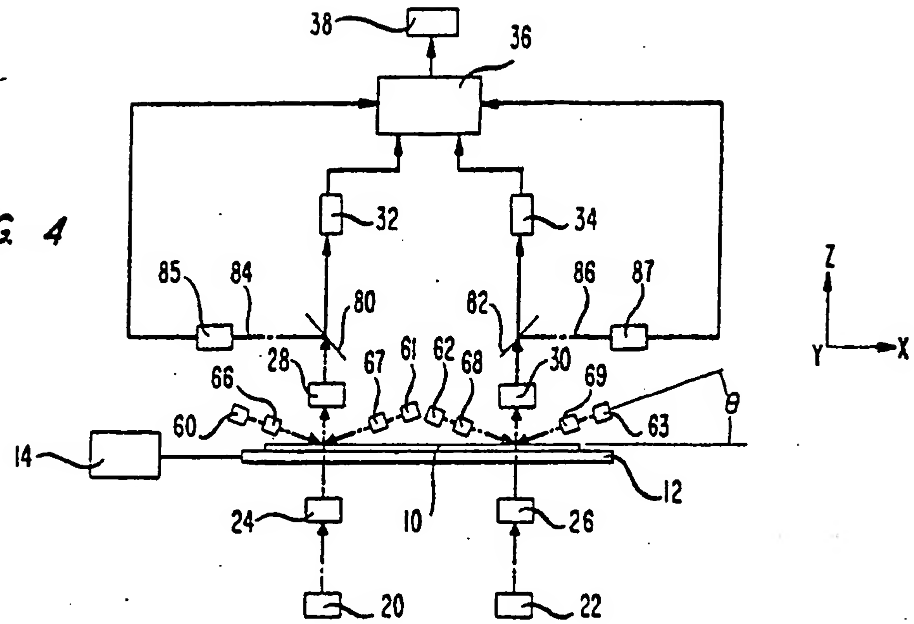


FIG. 5

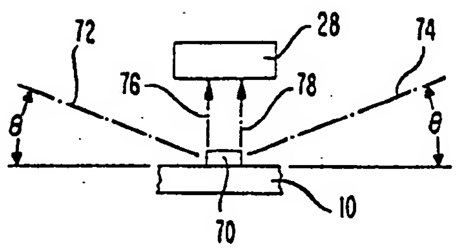


FIG. 6

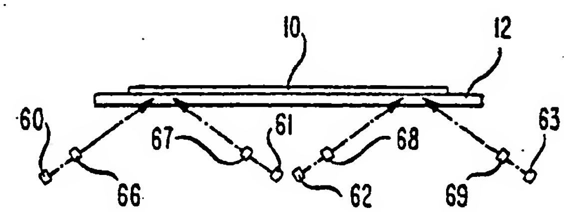


FIG. 7

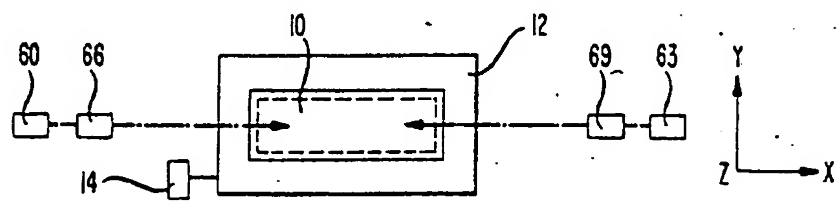
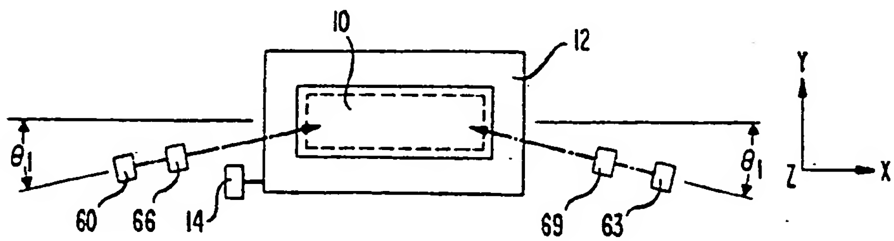


FIG. 8



INTERNATIONAL SEARCH REPORT

International Application No PCT/US 85/00082

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: G 01 N 21/88

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	G 01 N 21/88

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US, A, 4421410 (K. KARASAKI) 20 December 1983, see column 4, figure 6, lines 30-68 --	1,3,4,5,7, 9,10
X	Patents Abstracts of Japan, volume 7, no. 274, page 241 (1419) 7 December 1983 & JP, A, 58151544 (NIHON JIDOU SEIGYO) 8 September 1983, see the whole abstract --	1,2
X	Patents Abstracts of Japan, volume 6, no. 27, page 102 (905) 17 February 1982 & JP, A, 56146112 (MITSUBISHI DENKI) 13 November 1981, see the whole abstract --	1,5,7
A	IBM Technical Disclosure Bulletin, volume 23, no. 12, May 1981 New York (US) D. Wagner: "High resolution optical surface microtopography", pages 5422-5423, see the whole article --	1,7

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* Special categories of cited documents: [10]

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
2nd May 1985	07 JUIN 1985
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	G.L.M. Kruydenberg

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
A	IBM Technical Disclosure Bulletin, volume 13, no. 3, August 1970, New York (US) H. Rottmann: "Dark field illumination technique for mask defect examination", pages 670,671, see page 671, paragraps 1,2	1
A	FR, A, 1588231 (C. IND. DES LASERS) April 1970, see page 3, lines 16-28; figure 1	1
P,X	WO, A, 84/01212 (CONTREX INC.) 29 March 1984, see pages 8,9; lines 1-20; page 11, lines 25-32; page 12, figure 1	1,4,7,10
P,X	Patents Abstracts of Japan, volume 8, no. 55, page P-260 (1492) 13 March 1984, & JP, A, 58204344 (NIHON JIDOU SEIGYO) 29 November 1983, see the whole abstract	1,5,7
A	Japanese Journal of Applied Physics, volume 14, supplement 14-1, 1975, (JP) J. Cuthberth et al. "A microelectronic mask inspection system", pages 481-486, see page 481, right-hand column, page 482, figures 1,2,4	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/US 8500082 (SA 8844)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 29/05/85

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A- 4421410	20/12/83	JP-A- 56016804	18/02/81
FR-A- 1588231	10/04/70	None	
WO-A- 8401212	29/03/84	EP-A- 0119198	26/09/84

For more details about this annex :
see Official Journal of the European Patent Office, No. 12/82

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 4 : G01N 21/88	A1	(11) International Publication Number: WO 85/03353 (43) International Publication Date: 1 August 1985 (01.08.85)

(21) International Application Number: PCT/US85/00082

(22) International Filing Date: 16 January 1985 (16.01.85)

(31) Priority Application Number: 573,816

(32) Priority Date: 25 January 1984 (25.01.84)

(33) Priority Country: US

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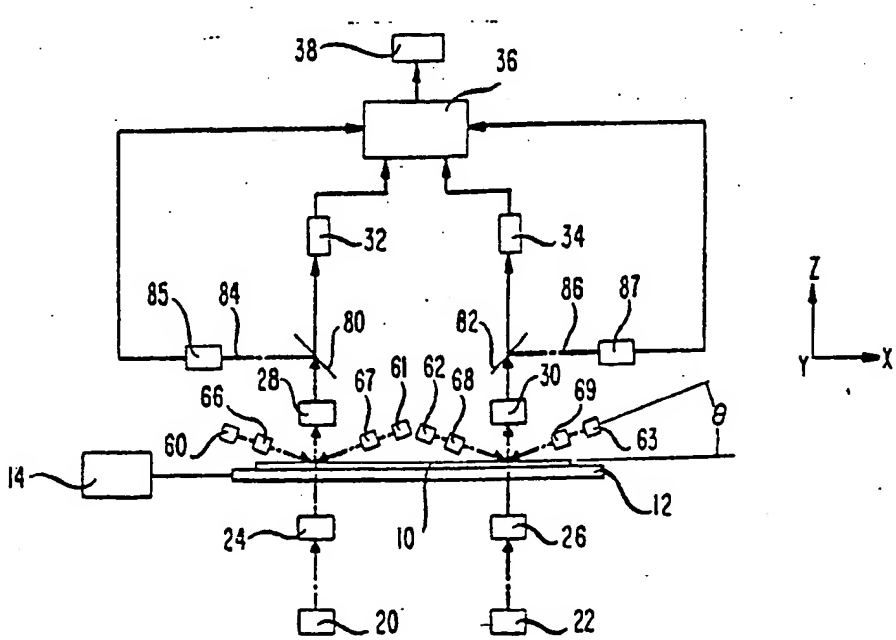
(81) Designated States: AT (European patent), BE (European patent), CH (European patent), DE (European patent), FR (European patent), GB (European patent), JP, LU (European patent), NL (European patent), SE (European patent).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: INSPECTION SYSTEM UTILIZING DARK-FIELD ILLUMINATION



(57) Abstract

For inspecting photolithographic masks, and the like, of the type comprising an ordered mosaic of identical patterns on a substrate (10) surface, corresponding portions or features (42, 44) of pairs of patterns are simultaneously illuminated by dark-field illumination (60-69) (incident light rays almost parallel to the surface) to cause light scattering from edges only of the features and of any defects associated therewith. The presence of a defect (40) in or at one of the features gives rise to a difference in the light scattering characteristic from the two features, which difference provides an error signal indicative of the presence of a defect.

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INSPECTION SYSTEM UTILIZING DARK-FIELD ILLUMINATION

Background of the Invention

This invention relates to methods and apparatus for inspecting patterned workpieces, particularly lithographic masks and reticles used in the fabrication of integrated circuit semiconductor wafers and/or for inspecting the wafers themselves.

Feature widths on masks and reticles used in making integrated circuits have continued to shrink, e.g., as low as 0.5 μm.

Ideally, workpieces such as masks, reticles and wafers should be inspected for defects down to about half the minimum feature size. In practice, though, this is often not possible. For example, one commercially available mask inspection system is capable of detecting a minimum-size defect of only about one μm, and this capability degrades to about two μm in complex areas of the mask under inspection. (Hereinafter, the term "mask" is to be construed to mean either a mask or a reticle. Also, the invention is applicable to the inspection of other patterned workpieces, e.g., semiconductor wafers.)

Conventional systems accomplish mask inspection by bright-field illumination of a portion of a pattern on the mask. A signal derived therefrom is compared with another signal representative of a corresponding portion of another supposedly identical pattern (both patterns, for example, along with many others, being disposed in an ordered mosaic on the mask). Because the patterns are supposedly identical, differences between the two signals are indicative that one of the portions is defective.

In practice, the minimum-size defect that can be detected by an inspection system of the aforespecified type is set by false error indications arising from misalignment between the patterns being compared. At a given misalignment, the minimum detectable defect is defined as the defect which produces a signal as large as the false

signal arising from the misalignment.

Misalignment between the patterns may arise from residual alignment errors in the inspection systems, mismatched optical distortions, mask distortions, linewidth variations, etc. The present invention is directed to means for reducing the effects of such misalignments.

Summary of the Invention

Workpiece patterns to be compared are illuminated in a dark-field mode in which incident light is directed at the surface of the workpiece at a glancing angle. In such a mode, only light scattered from the edges of a feature or defect is detected. For a given misalignment, the ratio of defect signal-to-misalignment signal for relatively small defects is found to be much greater with dark-field illumination than with conventional bright-field illumination. Hence, dark-field illumination in an inspection system provides a basis for greatly increasing the detectability of small defects.

Brief Description of the Drawing

FIG. 1 depicts a known mask inspection system;

FIG. 2 represents two compared mask areas one of which contains a defect;

FIG. 3 represents features in two compared mask areas and illustrates a misalignment therebetween;

FIG. 4 is a schematic representation of a mask inspection system in accordance with the present invention;

FIG. 5 shows the manner in which incident light is scattered by and collected from a feature or defect illuminated in the dark-field mode;

FIG. 6 shows an alternative way of providing dark-field illumination in the FIG. 4 system;

FIG. 7 is a top view of a portion of the FIG. 4 system; and

FIG. 8 is a top view of a portion of a modification of the FIG. 4 system.

Detailed Description

In the conventional system schematically depicted in FIG. 1, a standard workpiece 10 to be inspected is shown supported on a table 12. The table is mechanically coupled to an XY drive assembly 14.

For illustrative purposes, the workpiece 10 of FIG. 1 is a mask. The mask 10 comprises an optically transparent substrate having thereon optically opaque features, e.g., of chromium. These features define at least two supposedly identical patterns on the mask.

In the FIG. 1 system, two spots of light are directed along dot-dash reference lines 16 and 18 through openings through the table 12 at the underside of the mask 10. The spacing of the spots is equal to the pattern spacing, or a multiple thereof, so that the spots are directed at corresponding, presumably identical portions or features of identical patterns.

The light spots are provided by conventional sources 20, 22 and respectively associated lens assemblies 24, 26.

By means of the assembly 14, the table 12 of FIG. 1 is indexed in the X and Y directions for inspecting successive pairs of patterns on the mask.

The amount of incident light that is propagated through the mask 10 is dependent on the transmissive character of the pattern in each illuminated area.

In the conventional so-called bright-field-illumination mode represented in FIG. 1, light transmitted through the illuminated patterned areas of the mask 10 is collected by lens assemblies 28 and 30 which comprise, for example, conventional microscope objectives. In turn, this collected light is focused onto standard photodetector arrays 32 and 34 which provide electrical output signals representative of the illuminated mask patterns.

The signals provided by the arrays 32, 34 are compared and processed in a standard signal processor and minicomputer unit 36, and viewed from a display 38.

Assume that the viewing optics of the inspection

system are characterized by a Gaussian point spread function whose full-width at half maximum (FWHM) is w. (The value w also constitutes the so-called resolution element of the viewing optics.) Assume further that one of the spaced-apart patterns being inspected contains a centrally located opaque circular defect 40 of diameter d, as depicted in FIG. 2.

In the standard bright-field mode of mask illumination, it is apparent that the photodetector array responsive to light transmitted through the left-hand pattern that contains the opaque defect 40 (FIG. 2) receives less light than the other photodetector array. As a result, a bright-field difference signal B_{def} attributable to the defect 40 is generated in the unit 36 of FIG. 1. When d/w is small, B_{def} can be approximated by the expression

$$K_1 I_0 d^2 \qquad (1)$$

where K_1 is a constant and I_0 is the peak value of the point spread function at the photodetector array. (The constants K_1, K_2, K_3 and K_4 employed herein are roughly of the same order of magnitude.)

As mentioned above, difference signals are generated in the mask inspection systems even in the absence of defects. Thus, for example, relative misalignment between features in the patterns being compared also produces a difference signal. In practice, such misalignment-caused signals set the value of the minimum-size defect that can be detected by the inspection system.

FIG. 3 represents portions of two identical opaque features 42 and 44 included in spaced-apart patterns, each feature including a straight edge 46 and 48, respectively. With perfect alignment, the edges of the two features are disposed at identical corresponding points. Thus, for example, the right-hand edge 46, 48 of each ideal

feature would extend through the center 50, 52 of its respective light spot 54 and 56. In this ideal case, the transmitted light associated with each of the light spots 54, 56 would be exactly the same. Hence, no difference signal (false defect signal) would be thereby generated by the unit 36 of FIG. 1.

But, as specified earlier above, perfect alignment is rarely, if ever, achieved in practice. This is also represented in FIG. 3 wherein the edge of the feature 42 is assumed, because of misalignment by a distance "a" relative to the aforespecified ideal condition, to lie along dashed line 58.

As a consequence of such misalignment, the photodetector array responsive to bright-field light transmitted through the left-hand pattern receives less light than the other photodetector array. As a result, a bright-field difference signal B_{mis} attributable to the misalignment "a" is generated. When a/w is small, B_{mis} can be approximated by the expression

$$K_2 I_0 aw \qquad (2)$$

where K_2 is a constant.

Roughly speaking, when the speckled area in FIG. 3 attributable to misalignment approximately equals the area of the defect 40 of FIG. 2, the difference signal B_{mis} approximately equals the difference signal B_{def}. This is evident from a consideration of equations (1) and (2).

In one illustrative bright-field system in which w = 1 μm (Gaussian illumination) and d = 0.52 μm, B_{mis} approximately equals B_{def} for a misalignment "a" of about 0.2 μm. That is, in such prior art system, for a misalignment of about 0.2 μm, the minimum detectable defeat has a value of d = 0.52 μm.

In accordance with the present invention, the patterns being compared are illuminated in a dark-field

mode, as depicted in FIG. 4. By "dark-field" illumination is meant illumination in a non-normal, glancing direction. In effect, dark-field illumination outlines only the edges of features or defects on the mask. Because of this, when viewed from above, the mask surface (the "field"), although illuminated by incident light, appears dark except for visible bright lines corresponding to feature or defect edges.

In Fig. 4, the dark-field is provided by four light sources 60 through 63 and associated lens assemblies 66 through 69 which together serve to illuminate corresponding portions of two patterns on the mask 10.

Advantageously, for reasons later described, the illumination provided by the sources 60 through 63 is selected to be within a specified wavelength band. This is accomplished, for example, with a mercury arc lamp and an associated filter. Alternatively, each source can constitute a laser.

Advantageously, the angle θ at which light is directed at the mask 10 in the dark-field mode is in the range of 0-to-75 degrees. Illustratively, the angle θ is selected to be approximately 5 degrees.

For reasons later described, the FIG. 4 system also advantageously includes a bright-field-illumination capability of the type described above in connection with FIG. 1.

In the dark-field mode of operation, only light scattered from illuminated edges of a feature or defect is collected. Light incident on other surfaces of the features or defects is reflected and/or refracted along paths that do not fall within the entrance aperture of the collecting optics.

This is illustrated in FIG. 5, wherein feature or defect 70 on one pattern on the workpiece 10 is obliquely illuminated by light beams directed thereat along center lines 72, 74. Illustratively, each beam illuminates an area approximately 300 μm in diameter on the workpiece

surface.

Light scattered from the edges of the feature or defect 70 is represented by lines 76, 78. Only such scattered light is collected by the lens assembly 28.

Scattered light collected by the lens assemblies 28, 30 is directed (FIG. 4) at dichroic mirrors 80, 82. These mirrors reflect light of wavelength emitted by the dark-field-illumination sources 60 through 63. On the other hand, bright-field illumination provided by the sources 20, 22 at a different wavelength propagates straight through the mirrors 80, 82 to the photodetector arrays 32, 34. (Other known techniques such as polarization separation are available for separating bright-field and dark-field illumination.)

Dark-field-derived light reflected by the mirrors 80, 82 is propagated along paths 84, 86 to respective photodetector arrays 85, 87. In turn, electrical signals generated by the arrays 85, 87 are applied to the unit 36.

Considering, for example, the dark-field illumination of the two pattern portions shown in FIG. 2, the photodetector array 85 responsive to light from the left-hand portion that contains the opaque defect 40 receives more scattered light than does the photodetector array 87 which is responsive to light from the right-hand portion which contains no edges to scatter light toward the lens assembly 30 of FIG. 4. As a result, a dark-field difference signal D_{def} attributable to the defect 40 is generated. When d/w is small, D_{def} can be approximated by the expression

$$K_3 J_0 d \qquad (3)$$

where K_3 is a constant and J_0 is the intensity per unit length of the edge source of the scattered light. For very large centrally positioned defects (d/w>>1), D_{def} becomes small because the defect edge lies outside the

light spot.

For the particular misalignment condition represented in FIG. 3, assuming the light spots 54 and 56 are from the dark-field light sources 60-63, the length of the feature edge lying within the light spot 54 on the left-hand portion is less than the length of the feature lying within the light spot 56 on the right-hand portion. Hence, the photodetector array 87 responsive to scattered light from the right-hand portion receives more light than does the photodetector array 85 responsive to scattered light from the left-hand portion. As a result, a dark-field difference signal D_{mis} attributable to the misalignment a is generated in the unit 36 of FIG. 4. When a/w is small, D_{mis} can be approximated (for Gaussian illumination) by the expression

$$K_4 J_0 a \qquad (4)$$

where K_4 is a constant.

Significantly, for a given misalignment, the ratio of defect signal-to-misalignment signal is much greater for dark-field illumination than it is for bright-field illumination. This can be seen, for example, from FIG. 3. For a given misalignment "a", the misalignment signal B_{mis} for bright-field illumination is a function of the area aw (equation 2), whereas the misalignment signal D_{mis} for dark-field illumination is a function merely of the linear misalignment dimension "a" (equation 4). Although the strength of the defect signal is smaller for dark-field illumination than for bright-field illumination, still, as noted, the net result is that the ratio of defect signal to misalignment signal is greater with the dark-field illumination. In other words, for a given misalignment, a mask inspection system embodying dark-field illumination can detect defects that are considerably smaller than those detectable in a bright-field system.

In one specific illustrative dark-field system in which w = 1 μm and a = 0.2 μm (the same misalignment mentioned above for bright-field illumination), D_{def} approximately equals D_{def} when the diameter d of a defect has a value of only about 0.11 μm. Thus, in this particular example, the diameter of the minimum-size defect detectable in the dark-field inspection mode is less than four times that of the minimum-size defect detectable in the conventional bright-field mode. The gain in sensitivity with dark-field illumination is even greater for smaller misalignments.

In the system shown in FIG. 4, dark-field illumination of two spaced-apart regions on the mask 10 is achieved by utilizing sources 60 through 63 positioned above the surface of the mask. Alternatively, dark-field illumination can be implemented by positioning the sources and associated lens assemblies below the mask. A portion of a system that embodies this alternative approach is schematically depicted in FIG. 6.

FIG. 7 is a simplified top view of a portion of the FIG. 4 system. All the light from the dark-field light sources 60-63 (sources 61 and 62 not being shown) are directed along the X-axis of the table 12. In FIG. 8, the light sources are off-set by an angle θ_1 (not critical, but generally in a range of 1 to 20 degrees) from the X-axis. Generally (although a function of the geometry of the features on the workpiece), the arrangement of FIG. 8 has a greater defect detection sensitivity than that of the FIG. 7 arrangement. The reason is as follows.

The defect detect sensitivity is a function of the difference in the amount of light received from the two pattern features being inspected, such difference being caused by the presence of a defect (i.e., any difference between the features). The detection sensitivity can be increased if the proportion of the total light received by the light detectors owing to the presence of the defect is increased. This is accomplished in the FIG. 8

arrangement.

The amount of light scattered from a feature or defect edge in any direction is a function of the angle of incidence of the light with respect to the edge. Thus, for example, for feature edges aligned in the X and Y directions, the amount of light scattered in the X-Z plane towards the detector 28 (disposed in the X-Z plane, FIG. 4) is greater in the FIG. 7 arrangement than in the FIG. 8 arrangement owing to the differences in the angle of incidence of the illumination against the feature edges. Accordingly, for such feature edge orientations, the total amount of dark-field illumination reaching the detectors is less in the FIG. 8 arrangement than in the FIG. 7 arrangement. However, for defects, which generally have irregular shapes, the total amount of light scattered from the defect edges towards the light detectors is little affected by the angle θ_1 and, generally, the same amount of light will be scattered by the defect edges in the X-Z plane in either of the FIG. 7 and 8 arrangements. Thus, because the light scattered from the X-Y oriented feature edges towards the light detector in the FIG. 8 arrangement is less than that scattered from these feature edges in the FIG. 7 arrangement, the light scattered from the defect edges in the FIG. 8 arrangement is a larger proportion of the total light received by the detectors than in the FIG. 7 arrangement.

In practice, the vast majority of edges of features of most masks extend along preferred directions, e.g., along the X and Y axes shown in FIGs. 7 and 8. Thus, in such situations, the FIG. 8 arrangement provides greater defect detection sensitivity.

Although dark-field illumination greatly increases the detectability of small defects, it is generally advantageous to retain some bright-field capability even at a reduced sensitivity of the dark-field system. This is because the bright-field system is better able to detect large defects.

The inspection systems rely upon a comparison of the light from two patterns. Both patterns need not be on the same workpiece, and one of the patterns, where ever located, can be a standard against which the other patterns, one by one, are compared. Also, the standard can comprise simply a train of signals against which the detected signals are compared.

Claims

1. Apparatus for inspecting a workpiece to determine whether or not a first region thereof is patterned in accordance with prescribed design standards, said apparatus comprising--

means for illuminating said region to cause light to be transmitted therefrom,

means for collecting such transmitted light and providing a first output signal representative of the pattern of said region,

means for providing a comparison signal derived from a second region supposedly identical to said first region, and

means for comparing said signals to provide an indication of whether or not said first region is patterned in accordance with said second region and thus in accordance with said prescribed design standards,

characterized by means (60, 66, 67 61) for illuminating said first region (42) by dark-field illumination, said transmitted light thus comprising light scattered from edges (46) of said first region.

2. Apparatus as in claim 1 wherein said second region (44) is disposed on said workpiece, and said comparison signal is obtained using means (63, 69, 68, 62, 30, 82, 87) separate from but identical to the means used to provide said first output signal.

3. Apparatus as in claim 1 wherein said second region is disposed on another workpiece, and said comparison signal is obtained using means (63, 69, 68, 62, 30, 82, 87) separate from but identical to the means used to provide said first output signal.

4. Apparatus as in claim 1 wherein said comparison signal is a stored signal representative of said second region.

5. Apparatus as in claims 1-3 further including means (20, 24) for illuminating said first region in a bright-field mode,

means (32) responsive to bright-field-mode light transmitted from said first region for providing a second output signal also representative of the pattern of said first region, and

means (80) for distinguishing between dark-field-mode scattered light and bright-field-mode transmitted light for generating said first and second output signals in response to said scattered and transmitted light, respectively.

6. Apparatus as in claims 1-4 wherein different edges of said first region extend along preferred (x-y) axes, and wherein the direction (θ_1) of incident dark-field illumination is selected to minimize collectible light scattered from said edges.

7. A method of inspecting a workpiece to determine whether or not a first region thereof is patterned in accordance with prescribed design standards, said method comprising the steps of

illuminating said first region to cause light to be transmitted therefrom,

collecting such transmitted light for providing a first output signal representative of the pattern of said region,

providing a comparison signal derived from a second region supposedly identical to said first region

and comparing said signals to provide an indication of whether or not said first region is patterned in accordance with said second region and thus in accordance with said prescribed design standards,

characterized by illuminating said first region in a dark-field illumination mode.

8. A method as in claim 7 wherein said second region is disposed on said workpiece, and said comparison signal is obtained using method steps identical to those used to provide said first output signal.

9. A method as in claim 7 wherein said second region is disposed on another workpiece, and said

comparison signal is obtained using method steps identical to those used to provide said first output signal.

10. A method as in claim 7 wherein said comparison signal is a stored signal representative of said second region.

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FIG. 1
(PRIOR ART)

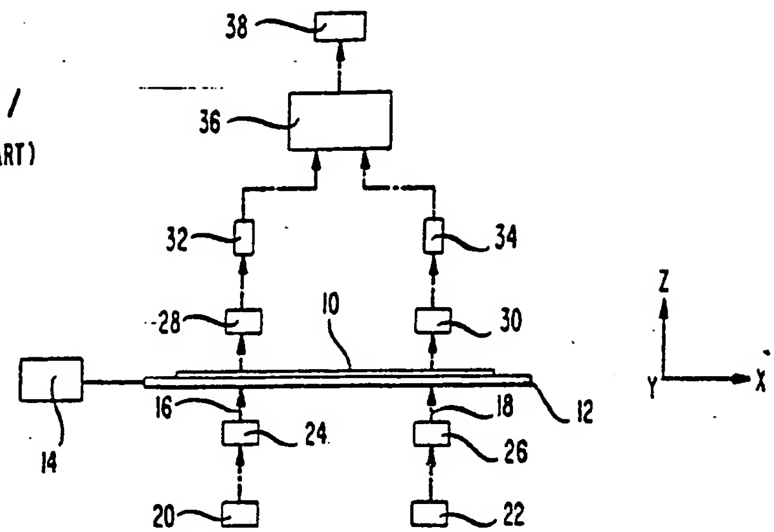

FIG. 2
SPACED-APART AREAS BEING COMPARED

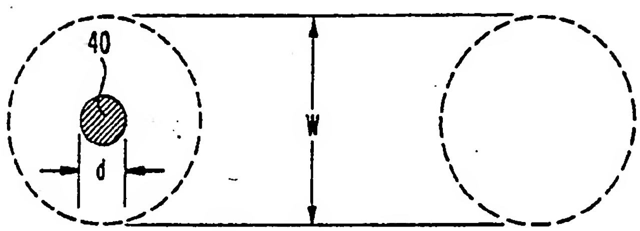

FIG. 3

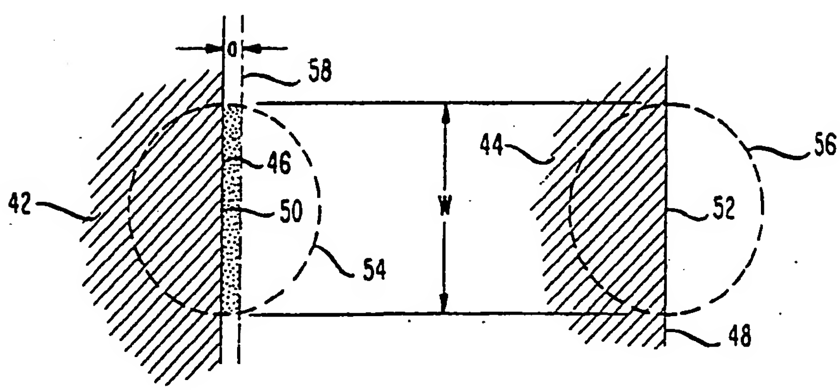

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FIG. 4

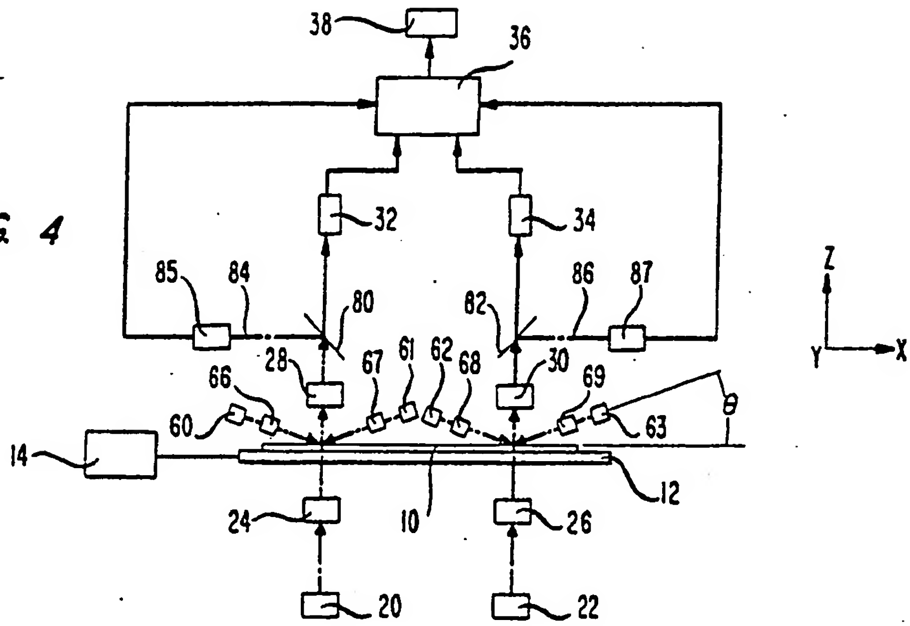


FIG. 5

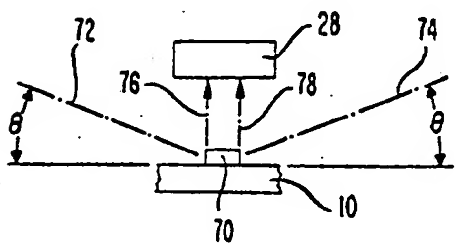


FIG. 6

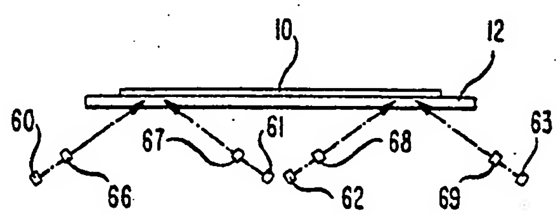


FIG. 7

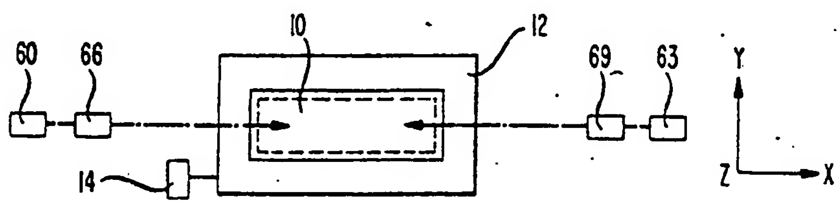
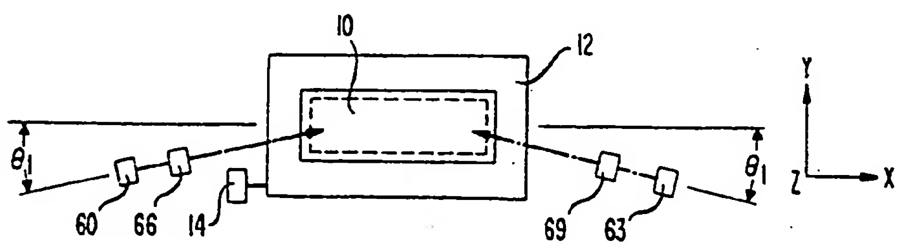


FIG. 8



INTERNATIONAL SEARCH REPORT

International Application No PCT/US 85/00082

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: G 01 N 21/88

II. FIELDS SEARCHED

Minimum Documentation Searched

Classification System	Classification Symbols
IPC^4	G 01 N 21/88

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched

III. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	US, A, 4421410 (K. KARASAKI) 20 December 1983, see column 4, figure 6, lines 30-68	1,3,4,5,7, 9,10
X	Patents Abstracts of Japan, volume 7, no. 274, page 241 (1419) 7 December 1983 & JP, A, 58151544 (NIHON JIDOU SEIGYO) 8 September 1983, see the whole abstract	1,2
X	Patents Abstracts of Japan, volume 6, no. 27, page 102 (905) 17 February 1982 & JP, A, 56146112 (MITSUBISHI DENKI) 13 November 1981, see the whole abstract	1,5,7
A	IBM Technical Disclosure Bulletin, volume 23, no. 12, May 1981 New York (US) D. Wagner: "High resolution optical surface microtopography", pages 5422-5423, see the whole article	1,7

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
2nd May 1985	07 JUIN 1985
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	G.L.M. Kruydenberg

Form PCT/ISA/210 (second sheet) (January 1985)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

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A	IBM Technical Disclosure Bulletin, volume 13, no. 3, August 1970, New York (US) H. Rottmann: "Dark field illumination technique for mask defect examination", pages 670,671, see page 671, paragraps 1,2	1
A	FR, A, 1588231 (C. IND. DES LASERS) April 1970, see page 3, lines 16-28; figure 1	1
P,X	WO, A, 84/01212 (CONTREX INC.) 29 March 1984, see pages 8,9; lines 1-20; page 11, lines 25-32; page 12, figure 1	1,4,7,10
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A	Japanese Journal of Applied Physics, volume 14, supplement 14-1, 1975, (JP) J. Cuthberth et al. "A microelectronic mask inspection system", pages 481-486, see page 481, right-hand column, page 482, figures 1,2,4	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/US 8500082 (SA 8844)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 29/05/85

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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WO-A- 8401212	29/03/84	EP-A- 0119198	26/09/84

For more details about this annex :
see Official Journal of the European Patent Office, No. 12/82